Preliminary Statistical ΔV Analysis for a Representative Europa Orbiter Mission

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The Europa Orbiter Mission will put a spacecraft in low altitude orbit around Europa to investigate the existence of a liquid ocean under the frozen surface. The trajectory consists of the interplanetary cruise phase, the Jovian tour and endgame phases, and the Europa orbital phase. The deterministic ΔV estimate for a representative trajectory to Europa is approximately 2000 m/s [Johannesen and D'Amario, 1999a]. This paper describes the methods used to estimate the additional ΔV capability required to account for errors attributed to launch vehicle injection, orbit determination (OD), and maneuver execution. The estimated statistical ΔV through the Europa Orbit Insertion (EOI) maneuver has a mean value of ~125 m/s with a 22 m/s standard deviation. The corresponding estimated 99 percent confidence ΔV is ~200 m/s, or 10% of the deterministic value. An injection covariance (provided by Lockheed Martin Astronautics) and simulated OD covariances are used to model injection and OD errors. Moreover, Gates' [1963] maneuver execution error model is used to model the effect of spacecraft attitude and propulsive uncertainties. A multiple maneuver optimization strategy in conjunction with a Monte Carlo method is used in order to assess the statistical ΔV requirements for the mission. Ongoing work includes the assessment of Europa orbital phase as well as new (and shorter) Jovian tour/endgame phases.

INTRODUCTION

Mission Objectives

The Europa Orbiter Science Definition Team (SDT) has defined a minimum set of objectives that must be satisfied. The primary (1A) objectives are [Chyba, 1998]:

- Determine whether or not a subsurface ocean exists
- Characterize the 3-D distribution of any subsurface liquid ocean and the overlaying ice layer

- Understand the formation of surface features including sites of recent or current activity, and identify candidate sites for future lander missions

Scope of this study

This work provides a summary of the navigation analysis for a representative Europa Orbiter Mission. The purpose of this study is to provide an overall assessment of the total statistical ΔV required to account for errors associated with launch vehicle (LV) injection, orbit determination (OD), and maneuver execution. The results presented here do not include the orbital (in orbit around Europa) phase of the mission. This is a work in progress and the results should be regarded as such.

The statistical Δv estimate for a given mission is based on a reference trajectory generated by the mission design team. Given a range of launch opportunities, mission planners start the design process by using a trajectory optimization program, CATO [Byrnes and Bright, 1995], to generate several trajectories leading to a number of arrival dates and conditions at Jupiter system [Johannesen and D'Amario, 1999a]. For each one of these arrival states, a number of coarse ballistic Jovian satellite tour trajectories are designed using simple conic solutions [Heaton et. al., 2000]. The tour trajectories consist of combinations of gravity assist flybys of the Galilean satellites (Io, Europa, Ganymede and Callisto) to reduce the energy of the spacecraft and lower the apojove distance. A number of the conic solutions which best satisfy mission constraints (e.g., minimum radiation dosage) are then selected for more detailed analyses. For each one of these tours, the design team may construct a number of endgame segments leading to Europa orbit injection. The endgame phase is characterized by consecutive Europa flybys and deterministic maneuvers that bring the spacecraft's orbit into near-resonance with Europa's orbit. CATO is used again to optimize these trajectories in order to minimize total deterministic ΔV for the mission. In the optimization process, equations of motion are integrated using accurate models of the solar system and the spacecraft to confirm the viability of these trajectories [Johannesen and D'Amario, 1999a]. One such trajectory was selected as a representative trajectory to carry out the statistical ΔV analysis described here.

REFERENCE TRAJECTORY

All candidate Europa Orbiter Mission trajectories are comprised of four phases - cruise, tour, endgame and Europa orbit. The trajectory used for this study, referenced as Tour 9902, was provided by Johannesen and D'Amario [1999b] and is described here. The interplanetary cruise phase starts from launch on November 10, 2003. A 350 km flyby of Ganymede (designated G0) on August 13, 2006, reduces the energy of the spacecraft in preparation for the capture maneuver. Only 13 hours later, at Jupiter closest approach distance of

12.5 R_J (R_J = Jupiter radius), a large (777 m/s) Jupiter Orbit Injection (JOI) maneuver puts the spacecraft into a highly elliptic, high-energy orbit around Jupiter. This ends the cruise phase and starts the tour phase of the mission (it must be noted that a minimum flyby altitude of 200 km is imposed on all satellite encounters during the tour and endgame phases). The tour phase is signified by the fact that it is *mostly ballistic*, i.e., there is only one small deterministic maneuver (12 m/s) at the apojove after the 5th satellite encounter (Europa5, or E5, flyby). The E13 encounter marks the end of the tour phase and starts the endgame phase. During this phase, a series of Europa flybys, combined with several deterministic maneuvers (ranging from 40 to 152 m/s) at Jupiter apoapses further reduce the spacecraft energy leading to a loose 3rd-body capture at the E19 encounter. This marks the end of the endgame phase. At E19, a 522 m/s Europa Orbit Insertion (EOI) maneuver puts the spacecraft in orbit around Europa starting the 30-day Europa orbital phase of the mission.

NAVIGATION ERROR SOURCES

In a perfect world, the launch vehicle would put the spacecraft precisely in the designed trajectory, the spacecraft would follow this trajectory, and all the predefined deterministic maneuvers would be executed without any errors. However, there are three main groups of errors, which introduce uncertainty in the navigation process. These are LV injection errors, OD errors, and maneuver execution errors. These will be discussed bellow.

1. Launch Vehicle Injection Error Model

The first contributor to statistical ΔV is the accuracy with which the launch vehicle/upper stage deliver the spacecraft into its interplanetary trajectory. The uncertainty in the spacecraft state at injection is represented by the injection covariance. The injection covariance used for this study was provided by Lockheed Martin Astrodynamics (LMA) in October of 1997 and assumes the following:

- Launch System: Atlas IIARS with Star 48V;
- Direct trajectory to Jupiter with launch on 12/8/2004;
- C3 = 82.7 km^2/sec^2, where C3 represents the injection orbit energy.

2. Orbit Determination Error Model

Because spacecraft trajectories cannot be determined perfectly, differences exist between the true path of the spacecraft and the path estimated through orbit determination. Therefore, maneuvers designed using imperfect OD solutions will introduce downstream trajectory errors, which need to be corrected with subsequent statistical maneuvers. Errors in OD solutions can be estimated by covariance analyses, whereby simulated tracking data, *a priori* uncertainties and dynamical models are used in programs (similar to operational OD software) to generate spacecraft orbit uncertainties mapped to various times.

OD Covariance Model

Tracking. Simulated radiometric (X-band 2-way Doppler and range) tracking passes were distributed equally between DSN tracking stations in the United States, Australia and Spain. Tracking was simulated from launch through EOI as specified in Table 1. Filter weights for the simulated tracking were 1 mm/s for 60 sec compression Doppler data and 20 m for range data.

Filter Setup. The filter setups for the cruise and tour/endgame phases are described in Tables 2 and 3, which list the estimated and considered parameters along with their *a priori* uncertainties. Considered parameters are used to account for systematic errors in modeling which cannot be improved by the filter. The tour/endgame covariance analysis was performed in segments, with each segment *i* starting 5 days prior to encounter *i – 1*, and ending 1 day past encounter *i*.

Table 1: Schedule of Simulated Tracking Coverage

Interplanetary Cruise Phase	
Around TCMs	2 passes per day ± 4 days around TCMs
Launch to Launch + 14 days	Continuous
Launch + 14 days to Launch + 28 days	1 pass per day
Launch + 28 days to JOI – 90 days	1 pass per week
JOI – 90 days to JOI – 30 days	1 pass per day
JOI – 30 days to JOI – 3 days	2 passes per day
JOI – 3 days to JOI + 9 days	Continuous
JOI + 9 days to PJR	1 pass per day
Tour/Endgame Phases	
Around encounters	Continuous tracking ± 2 days around encounters
Around TCMs	Continuous tracking ± 1 day around TCMs
PJR to EOI - 90 days (i.e., tour phase)	1 pass per day
EOI - 90 days to EOI (i.e., endgame phase)	Continuous

*Note: TCM = Trajectory Correction Maneuver, JOI = Jupiter Orbit Insertion, PJR = Perijove Raise Maneuver, EOI = Europa Orbit Insertion

Table 2: Filter Setup, Cruise Phase

Estimated Parameters	*A-Priori* 1-sigma Uncertainty
Spacecraft epoch position and velocity	Infinite
Constant non-gravitational acceleration	1.0×10^{-11} km/s^2 per axis
Maneuvers	
• Injection + 15 days	1.5% of 50 m/s per axis
• DSM	1.5% of 230 m/s per axis
• DSM + 30 days	1.5% of 3.5 m/s per axis
• G0 - 200 days	1.5% of 3 m/s per axis

• G0 - 20 days	1.5% of 3 m/s per axis
• G0 - 5 days	1.5% of 3 m/s per axis
• JOI	1.5% of 777 m/s per axis
• JOI + 3 days	1.5% of 12 m/s per axis
• PJR	1.5% of 26 m/s per axis
Solar Pressure (area, reflectivities)	20% of nominal values
Jupiter planet ephemeris	DE-405 precursor
Jupiter GM, J2, J4, pole	From E5 Theory
Jupiter satellite ephemeris, including satellite masses	From E5 Theory
Stochastic Parameters	*A-Priori* 1-sigma Uncertainty
Non-gravitational acceleration (1-day updates, white noise)	1.0 x 10^{-11} km/s^2 per axis
Considered Parameters	*A-Priori* 1-sigma Uncertainty
Earth-Moon barycenter ephemeris	DE-405 precursor
Station Locations	0.5 m per axis
Troposphere (dry/wet)	1 cm, 4 cm
Ionosphere (day/night)	75 cm, 15 cm

Table 3: Filter Setup, Tour/Endgame Phases

Estimated Parameters	*A-Priori* 1-sigma Uncertainty
Spacecraft epoch position and velocity for each segment	1000 km, 100 m/s
Constant non-gravitational acceleration	1.0 x 10^{-11} km/s^2 per axis
Maneuvers	
• PJR + 10 days	1.5% of 3 m/s per axis
• Encounter – 1 day	1.5% of 3 m/s per axis
• Encounter + 1 day	1.5% of 5 m/s per axis
• Apojove and other maneuvers	The larger of: 1.5% of nominal magnitude per axis or 1.5% of 5 m/s per axis
Jupiter planet ephemeris	DE-405 precursor
Jupiter GM, J2, J4, pole	From E5 Theory
Jupiter satellite ephemeris, including satellite masses	From E5 Theory
Stochastic Parameters	*A-Priori* 1-sigma Uncertainty
Non-gravitational acceleration (1-day updates, white noise)	1.0 x 10^{-11} km/s^2 per axis
Considered Parameters	*A-Priori* 1-sigma Uncertainty
Earth-Moon barycenter ephemeris	DE-405 precursor
Station Locations	0.5 m per axis
Troposphere (dry/wet)	1 cm, 4 cm
Ionosphere (day/night)	75 cm, 15 cm

Outputs. OD covariances were generated for various times prior to each Trajectory Correction Maneuver (TCM) in support of the ΔV analysis. For the cruise phase, covariance matrices were computed for maneuver - 1 day, maneuver - 3 days and maneuver - 5 days data cutoffs. For the tour/endgame phase, data cutoff times were as follows: for the encounter + 1 day maneuvers, data cutoff times were at encounter + 2 hrs, encounter + 4 hrs, encounter + 6 hrs and encounter + 8 hrs; and for all other maneuvers, data cutoff times were at maneuver - 1 day, maneuver - 2 days and maneuver - 3 days. OD covariances were mapped to the B-plane of the next encounter in EME2000 coordinates. An exception to this was for the final segment of the endgame (i.e., ending with EOI), where covariances were mapped as conic elements (instead of B-plane) in EME2000 coordinates since the approach to Europa at EOI is not hyperbolic but elliptic.

3. Maneuver Execution Error Model

The third source of error in navigating a spacecraft is maneuver execution errors. Propulsive execution errors depend on several factors including (but not limited to):

- Knowledge and ability to control the orientation of the spacecraft;
- Knowledge of the orientation of the propulsion system relative to the spacecraft frame;
- Knowledge of the thrust vector delivered by the engines with respect to the thruster axes.

The combined effect of these uncertainties is that the achieved ΔV is different from the desired (commanded) ΔV. The vector difference between the two (Figure 1) is defined as the maneuver execution error and is broken up into 2 components. The component parallel to the desired ΔV is the magnitude error and the component perpendicular to it is the pointing error. Each one of these components is further decomposed into two parts. The fixed part, which is the same regardless of the size of the maneuver, and the proportional part, which is proportional to the ΔV size. To model the maneuver execution errors, each one of the 4 parts is treated as a scalar random variable with a Gaussian distribution $(0,\sigma^2)$. The fixed parts are given in velocity units, the proportional magnitude part in percent (relative to desired ΔV), and the proportional pointing error in radians [Gates, 1963].

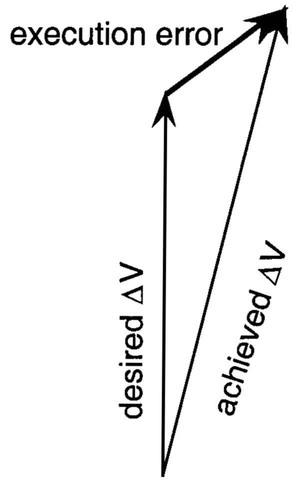

Figure 1: Maneuver execution error

The spacecraft propulsion system includes a main engine, a set of 22 Newton (22N) reaction control system (RCS) thrusters, and a set of 0.9N RCS thrusters. The 4 components of the execution error model are different for the different thruster systems. Table 4 presents the execution error model used for this study [Lee, 1999a,b] (it is assumed the 0.9N RCS thrusters are only used for attitude control). It must be noted that the 0.2% (1σ) main engine proportional magnitude error assumes an accelerometer controlled shut-off, while the 2.0% (1σ) RCS proportional magnitude error assumes a timer controlled shut-off (the latter is less accurate). It is assumed that all TCMs larger than 5 m/s in magnitude are performed by the main engine (458 N engine). All other TCMs, including those as small as 1 cm/s, are performed by the 22N RCS thrusters.

Table 4: Execution errors for the main engine and 22N RCS thrusters

Thruster System	1 σ Pointing Error (per axis)		1 σ Magnitude Error	
	Fixed (m/s)	Proportional (mrad)	Fixed (m/s)	Proportional (%)
Main Engine	0.012	6.0	0.0083	0.2 *
RCS (22N)	0.0035	12.0	0.0035	2.0
* For the 1st TCM (i.e., prior to engine calibration) a value of 0.5 is used.				

SOLUTION METHOD

To study the effect of navigation errors on total mission ΔV requirements, the nominal trajectory must be perturbed and the perturbed trajectory must be reoptimized. This process is repeated a large number of times in order to obtain meaningful statistical information on ΔV. Reoptimizing the nonlinear equations of motion, which requires repeated integration of the n-body problem, would be computationally very expensive. To eliminate this, the problem is linearized with respect to the nominal trajectory by numerically computing partial derivatives of the spacecraft state at target states (e.g., flyby conditions) with respect to perturbations at maneuver times along the nominal trajectory. A linear least-squares method is then used to minimize the total mission ΔV for each perturbed new trajectory.

Given the OD assumptions, and the resulting OD covariance matrices mapped to each upcoming target body, a series of Monte Carlo simulations were performed to generate ΔV statistics for the mission up to the orbital phase. Each simulation consists of 1000 perturbed trajectories, a sample size large enough to give a near Gaussian distribution for the OD and Execution errors used to compute a ΔV estimate (note that ΔV distribution itself is not Gaussian). To generate a perturbed trajectory, a random number generator and the OD covariance are used to alter the nominal state at a given maneuver time. This leads to a miss at the upcoming target. To correct this miss, the optimizer recomputes the ΔV for that maneuver, and all the subsequent maneuvers, in order to minimize the remaining total ΔV. A random number generator and the maneuver execution errors are then used to corrupt and execute the current commanded ΔV. This process is repeated until the last maneuver is performed and a new total ΔV computed. For each simulation, the mean, standard deviation, and 90, 95, and 99 percentile confidence intervals for individual, as well as total ΔV, are computed. Moreover, statistics on error ellipse delivery at each target are computed (Appendix A).

FLIGHT PATH CONTROL STRATEGY

The combination of OD and maneuver execution errors determine (or affect) not only the total statistical ΔV magnitude, but also how well the target conditions can be achieved. There are two other factors that affect the overall statistical ΔV and target delivery accuracy. One is the number and placement of the clean-up (statistical) trajectory control maneuvers (TCM). The other is the availability (timing) of OD information prior to a given TCM.

The trajectory design team determines the optimum number and placement of deterministic maneuvers needed to deliver the spacecraft to its target(s). In the absence of OD and execution errors, deterministic TCMs alone would be sufficient to control and maintain the nominal trajectory. However, due to OD and execution errors, the spacecraft will always deviate from its nominal course. The flight path control analyst, on the other hand, determines the nominal number and placement of clean-up (statistical) maneuvers to control (correct) the trajectory and deliver the spacecraft to its targets as precisely as possible. The standard approach is to place a clean-up TCM shortly after each large deterministic maneuver. Moreover, since the purpose of each satellite flyby is to adjust the spacecraft state (energy and direction), if the probe is off course, the desired change will not be achieved by the flyby. Therefore, a TCM is planned for shortly before each encounter to retarget the spacecraft to the pre-determined target conditions (e.g., flyby distance). Also, since the flyby conditions are almost never precisely met (therefore the desired change is not achieved), a TCM is planned for shortly after each encounter as well. These two TCMs are called the pre- and post-encounter TCMs, respectively (Figure 2). Satellite flybys are numbered incrementally. For instance, E5 and C6 refer to satellite flyby numbers 5 and 6, which occur at Europa and Callisto, respectively. Orbits around Jupiter are also numbered incrementally starting with the first apojove after JOI. Orbit number i starts shortly after one Jupiter apoapsis and ends at the next one. Other orbit events and TCMs are named relative to spacecraft orbit numbers and flyby bodies. Following this convention, E5-1 and E5+1 refer to pre- and post-encounter maneuvers at 1 day before and 1 day after the E5 encounter, respectively. Similarly, C10+apo refers to a TCM at the first apojove after C10 encounter (if a TCM occurs after the first apojove following an encounter, the orbit number is appended to the word apo, e.g., E18+apo26, which occurs at the third apojove after E18). It should be noted that during operations if the spacecraft is on course when approaching a statistical TCM, the TCM is skipped.

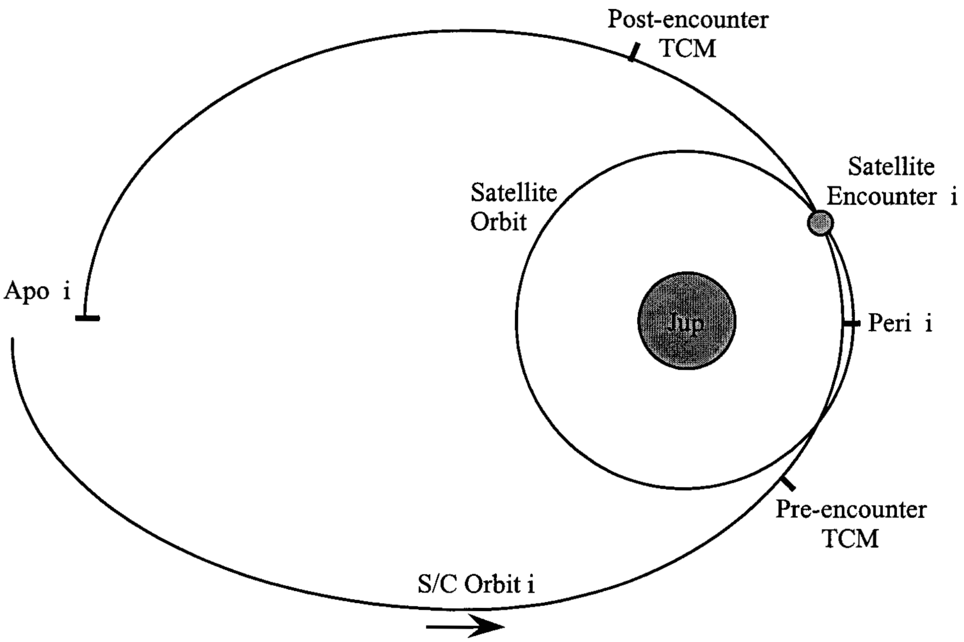

Figure 2: TCM positioning and orbit and TCM naming convention.

The orbits around Jupiter, from the start of the tour phase to the end of the endgame phase, consistently reduce in size (energy). Hence, the single pre- and post-encounter TCM strategy cannot be used for all situations. The first orbit around Jupiter (from the initial Ganymede encounter, G0, to the first Ganymede encounter after JOI, G1), is a 200-day orbit with one deterministic maneuver (perijove raise, PJR) at apoapsis. That is, there are 100 days between PJR and G1. Small deviations in the trajectory after PJR propagate to very large deviations 100 days later at G1. Hence, one pre-encounter TCM strategy results in very large ΔV values for both pre- and post-G1 encounter TCMs. Two additional TCMs after PJR prior to G1 pre-encounter maneuver have been designed to control the trajectory and reduce total ΔV. A different trajectory control problem arises during the endgame phase, where the spacecraft completes multiple revolutions around Jupiter between satellite encounters. At the end of this phase, the spacecraft orbit periods about Jupiter are less than 5 days. The spacecraft orbits Jupiter 5 times between the last two Europa encounters (prior to being captured by Europa at EOI). There is only one deterministic (E18+apo26) TCM at the third of the 5 apojoves after E18. Waiting until the E19 pre-encounter maneuver to correct the errors would be too costly. Hence, an extra TCM is designed at the following apojove (apo27) to correct the trajectory. This reduces the size of E19 pre-encounter TCM considerably. Table 5 shows the latest iteration of maneuver design strategy used for this study. In this iteration, some of the pre-encounter TCMs have been moved to earlier times (e.g., encounter – 3 days) to reduce the corresponding ΔV size. Columns 1 and 2 show the event or TCM and the corresponding date and time. Note that the letter A after an encounter name, e.g., G16A, refers to a non-targeted encounter. A non-targeted encounter is one which is not desired, occurs on the same orbit as a targeted encounter, the encounter conditions are not controlled, and usually occurs at much higher distances from the encounter body.

For a given TCM, it is always desirable to have the latest OD solution for the spacecraft and the target satellites. From an operational point of view, the necessary sequence of events from getting OD measurements to executing a TCM requires a minimum length of time. These events include obtaining OD measurements, solving for the OD solution, using the solution to redesign (re-optimize) the upcoming TCMs, and finally uplinking the new TCM sequence and executing it. This sequence dictates the minimum turn-around time. However, if the spacecraft is not near a body (i.e., near a flyby), and there has been enough time and observations since the last TCM, the OD solution is stable and does not change significantly. Hence, for operational convenience, one can allow more time between an OD solution and the upcoming TCM. Column 3 of Table 5 shows the time (in days) since the last TCM and Column 4 shows the OD data cut-off points (in days) relative to each TCM. In general, all pre-encounter TCMs have a TCM-1 day cut-off time and all post-encounter TCMs have a TCM-18 hour cut-off time. Except in a few specific cases, all other TCMs have a TCM -3 to -5 day cut-off point.

Table 5: Maneuver design strategy for 9902 trajectory; deterministic ΔVs are in bold and statistical ΔVs are in bold italic. ED and BPM refer to Earth Departure and Broken Plane Maneuver, respectively. (continued on following page)

Event / TCM	Date and Time (ET)	Days Since TCM	OD Cut-off (days)
Launch : ED	10-Nov-03		
ED + 15	20:00 Nov-03		-5.00
BPM	02:00 Aug-04	261.5 0	-5.00
BPM+3 0	12:00 Sep-04	30.00	-5.00
G0-200	24:00 Jan-06	500.3 3	-5.00
G0-20	23:57 Jul-06	180.0 0	-5.00
G0-5	07:57 Aug-06	15.00	-2.00
G0	12:57 Aug-06	h=35 0	
JOI	13:57 Aug-06	(km) 5.57	-1.00
JOI + 4	09:74 Aug-06 09:34	4.00	-1.00
PJR	13-Dec-06	117.6 0	-3.00
PJR+ 39	20:00 Jan-07	39.00	-3.00
G1-10	00:00 Feb-07	28.79	-3.00
G1 - 3	23:03 Feb-07	7.00	-1.00
G1	28:03 Feb-07	h=53 0	
Jup Peria p1	09:03 Mar-07		
G1 + 1	03:55 Mar-07	4.00	-0.75
Jup Apo	02:57 Apr-07		
G1 +	08:51 Apr-07	32.04	-3.00
G2o - 3	07:48 May-07	28.34	-1.00
G2	04:52 May-07	h=11 D	
Jup Peria p2	05:52 May-07		
G2 + 1	09:15 May-07	4.00	-0.75
Jup Apo	23:50 May-07		
G2 +	21:57 May-07	17.81	-3.00
G3o - 3	05:15 Jun-07	13.96	-1.00
G3	08:21 Jun-07	h=28 7	
Jup Peria p3	09:21 Jun-07		
G3 + 1	09:14 Jun-07	4.00	-0.75
Jup Apo	20:19 Jun-07		
G3 +	20:01 Jun-07	10.73	-3.00
G4o - 3	23:13 Jun-07	6.75	-1.00
G4	00:13 Jun-07	h=28 6	
Jup Peria p4	07:13 Jul-07		
G4 + 1	06:15 Jul-07	4.00	-0.75
Jup Apo	03:50 Jul-07		
G4 +	06:10 Jul-07	13.88	-3.00
E5o - 1	26:55 Jul-07	13.15	-1.00
Jup Peria p5	29:27 Jul-07		
E5	29:32 Jul-07	h=20 0	
E5 + 1	30:27 Jul-07	2.00	-0.75
Jup Apo	00:33 Aug-07		
E5 +	08:28 Aug-07	8.98	-3.00
C6o - 1	03:58 Aug-07	6.85	-1.00
C6	06:28 Aug-07	h=39 D	
C6 + 1	09:28 Aug-07	2.00	-0.75
Jup Peria p6	06:28 Aug-07		
Jup Apo	30:03 Aug-07		
C6 +	00:74 Aug-07	12.94	-3.00
G7o - 1	05:01 Sep-07	9.60	-1.00
G7	09:28 Sep-07	h=18 D	
Jup Peria p7	18:28 Sep-07		
G7 + 1	18:18 Sep-07	2.00	-0.75
Jup Apo	19:26 Sep-07		
G7 +	09:28 Sep-07	8.41	-3.00
E8o - 1	25:17 Sep-07	7.64	-1.00
Jup Peria p8	29:54 Sep-07		
E8	24:56 Sep-07	h=10 89	
E8 + 1	29:54 Sep-07	2.00	-0.75
E8 +	06-Oct-07	7.62	-3.00
Jup Apo	06:37 Oct-07		
E9 - 1	14:38 Oct-07	8.08	-1.00
Jup Peria p9	15:28 Oct-07		
E9	08:28 Oct-07	h=37 3	
E9 + 1	16:28 Oct-07	2.00	-0.75
Jup Apo	23:26 Oct-07		
E9 +	23:07 Oct-07	7.04	-3.00
Jup Peria p10	31:28 Oct-07		
C10 - 1	02:11 Nov-07	9.58	-1.00
C10	03:20 Nov-07	h=54 8	
C10 + 1	04:20 Nov-07	2.00	-0.75
Jup Apo	04:18 Nov-07		
C10 +	20:42 Nov-07	7.76	-3.00
G1o1 - 1	22:51 Nov-07	10.84	-1.00
Jup Peria p11	22:48 Nov-07		
G1 1	23:37 Nov-07	h=77 3	
G1 1 +	28:48 Nov-07	2.00	-0.75
Jup Apo	29:43 Nov-07		
G1 1 +	29:55 Nov-07	5.22	-3.00
G1o2 - 1	03:56 Dec-07	7.09	-1.00
Jup Peria p12	02:08 Dec-07		
G1 2	08:57 Dec-07	h=17 9	
G1 2 +	09:08 Dec-07	2.00	-0.75
Jup Apo	02:09 Dec-07		
Jup Peria p13	19:52 Dec-07		
Jup Apo	23:38 Dec-07		
G1 2 +	23:38 Dec-07	14.23	-3.00
E1o3 - 1	27:35 Dec-07	4.49	-1.00
Jup Peria p14	28:20 Dec-07		
E1 3	28:03 Dec-07	h=11 32	
E1 3 +	29:20 Dec-07	2.00	-0.75
E1 3 +	03:26 Jan-08	4.20	-3.00
Jup Apo	03:10 Jan-08		
E1 4 - 1	07:1 Jan-08	4.52	-1.00
Jup Peria p15	08:13 Jan-08		
E1 4	08:12 Jan-08	h=20 0	
E1 4 +	09:13 Jan-08	2.00	-0.75
E1 4 +	12:13 Jan-08	3.06	-3.00
Jup Apo	14:09 Jan-08		
G1 4 A - 1	14:00 Jan-08	2.30	-1.00
G1 4 A	25:19 Jan-08	h=21 82	
G1 4 A+	26:19 Jan-08	2.00	-0.75
Jup Peria p16	27:2 Jan-08		
G1 4 A-	21:3 Jan-08	4.62	-3.00
Jup 5 Apo	22:1 Jan-08		
E1 5 - 1	24:28 Jan-08	3.35	-1.00
E1 5	29:3 Jan-08	h=20 0	
Jup Peria p17	20:3 Jan-08		
E1 5 +	26:19 Jan-08	2.00	-0.75
G1 5 A	29:38 Jan-08	h=94 60	
E1 5 +	29:19 Jan-08	2.76	-3.00
Jup Apo	29:16 Jan-08		
E1 6 - 1	05:49 Feb-08	2.83	-1.00
Jup Peria p18	02:44 Feb-08		
E1 6	02:04 Feb-08	h=20 0	
E1 6 +	09:44 Feb-08	2.00	-0.75
G1 6 A	03:48 Feb-08	h=15 00	
G1 6 A+	04:51 Feb-08	1.32	-0.75
Jup Apo	08:51 Feb-08		

Table 5 (continued): Maneuver design strategy for 9902 trajectory; deterministic ΔVs are in bold and statistical ΔVs are in bold italic

Event/ TCM	Date and Time (ET)	Days Since Last TCM	OD Cut-off (days)
Jup Periap 19	07-Feb-08 23:26		
E16 + apo19	10-Feb-08 21:50	6.14	-3.00
Jup Apoap 19	10-Feb-08 21:58		
Jup Periap 20	13-Feb-08 21:02		
Jup Apoap 20	16-Feb-08 20:04		
E17 - 1	18-Feb-08 13:50	7.67	-1.00
E17	19-Feb-08 13:50	h=207.5	
Jup Periap 21	19-Feb-08 23:59		
E17 + 1	20-Feb-08 13:55	2.00	-0.75
Jup Apoap 21	22-Feb-08 08:04		
Jup Periap 22	24-Feb-08 16:15		
Jup Apoap 22	27-Feb-08 00:30		
E17 + apo22	27-Feb-08 00:43	6.45	-3.00
Jup Periap 23	29-Feb-08 10:25		
Jup Apoap 23	02-Mar-08 20:27		
E18 - 1	04-Mar-08 04:59	6.18	-1.00
Jup Periap 24	05-Mar-08 04:39		
E18	05-Mar-08 04:59	h=200	
E18 + 1	06-Mar-08 05:02	2.00	-0.75
Jup Apoap 24	06-Mar-08 22:58		
Jup Periap 25	09-Mar-08 01:18		
Jup Apoap 25	11-Mar-08 03:46		
Jup Periap 26	13-Mar-08 06:20		
E18 + apo26	15-Mar-08 08:24	9.14	-3.00
Jup Apoap 26	15-Mar-08 08:48		
Jup Periap 27	17-Mar-08 12:38		
Jup Apoap 27	19-Mar-08 16:27		
Jup Periap 28	21-Mar-08 20:14		
E18 + apo28	24-Mar-08 00:03	8.65	-2.00
Europa Periap	26-Mar-08 04:49		
E19 - 1	26-Mar-08 13:43	2.57	-1.00
Jup Periap 29	26-Mar-08 15:40		
Europa Apoap	26-Mar-08 22:34		
Jup Apoap 29	27-Mar-08 11:21		
E19	27-Mar-08 16:07	h=200	
EOI	27-Mar-08 16:07	1.10	-0.75

RESULTS AND DISCUSSION

A maneuver design strategy has been analyzed for a representative Europa Orbiter Mission. The analysis includes the interplanetary cruise, and the Jovian tour and endgame phases of the mission. Table 6 shows the deterministic, as well as the statistical mean, standard deviation, and 99% confidence interval estimated values of ΔV for the cruise phase (TCM's through JOI cleanup), the combined tour/endgame phase, and the mission total. The last column shows the required statistical ΔV (99% value - deterministic value) to account for injection, OD, and execution errors. (Note that although mission total values for the "deterministic" and the "mean" columns are obtained by adding the values in the first two rows, the same method cannot be used for the "σ", "99%", and "statistical" columns.) Given the assumptions discussed in the previous sections, the overall current best estimate of the statistical ΔV for the mission (excluding the orbital phase) is 197 m/s. Finally, adding the initial estimate of 20 m/s for the orbital phase, the total statistical ΔV for the mission is 217 m/s. This is well within the acceptable range of the initial estimate of 200 m/s for the mission.

Table 6: Statistical ΔV results for the Europa Orbiter 9902 trajectory

Mission Segment	ΔV (m/s)				
	Deterministic	Mean	1 σ	99%	Statistical
Cruise	1008	1022	15	1064	56
Tour/Endgame	969	1092	16	1140	168
Overall	1977	2114	22	2174	197

The current estimate of the statistical ΔV is very preliminary and depends on a number of assumptions, some of which are conservative, while others may be optimistic. These assumptions, their probable variations, and the effect they will have on the overall statistical ΔV are discussed here. The injection covariance estimate used in this study is nearly 3 years old and is based on a set of performance criteria for a Centaur and Star 48V stack. Lee [1999c] recently updated the Star 48V performance characteristics. The new pointing accuracy (per axis for pitch and yaw) and proportional magnitude are 21 mrad and 1%, respectively (compared to the old values of 7 mrad and 0.75%). While this change will increase the statistical ΔV (by primarily increasing the post injection TCM), it is difficult to quantify the increase without a new estimate from LMA for the injection covariance. However, it may be possible to qualitatively assess the increase by doing a parametric study by scaling the existing injection covariance. For instance, a 50% increase in LV injection uncertainty causes a 21 m/s increase in statistical ΔV estimate.

Further analysis of certain OD assumptions may result in decisions to change them in future studies. In particular, the use of RCS thrusters versus reaction control wheels for attitude deadbanding is still uncertain in the spacecraft design. The decision to go with one or the other for the entire mission, or split their use among different phases of the mission, will have a significant effect on the assumptions made regarding non-gravitational accelerations. Future parametric studies will provide some understanding in regard to statistical ΔV sensitivity with respect to OD assumptions.

Propulsive execution errors used for this study have been conservative in some regards and optimistic in others. Assuming a maximum 10 angle between the thrust vector and the sensing axis of the accelerometer, the execution error criteria used here are conservative. The values used primarily represent the requirements and not the capabilities (the capabilities are, for the most part, better than the requirements). However, if the accelerometer to thrust-vector angle remains at 35 (current spacecraft design baseline), although RCS execution errors will not change significantly, main engine proportional magnitude error will be worse than the requirement (Lee, 1999a,b). This means the execution error assumptions used are optimistic, and hence the statistical ΔV

estimate will increase. To assess the effect of degraded execution errors, the proportional magnitude error for the main engine was doubled, from 0.6% to 1.2% (3σ). The statistical ΔV increased by ~26 m/s, clearly exceeding the initial statistical ΔV budget.

TCM Contingency Analysis

The next step in maneuver analysis is to determine which, if any, of the navigation events in the mission are critical. That is, for a given nominal trajectory, how long can each TCM be delayed before recovery becomes impossible and the mission will be lost. The delay can happen if, for instance, hardware failure at the start of (or during) a TCM inhibits the successful completion of a maneuver. A complete contingency analysis of each TCM has not been performed yet. A limited contingency analysis of the representative trajectory, which includes delaying E18+apo19, E21+apo22, and E24+apo26 deterministic TCMs has been carried out. The results show that E18+apo19 can be delayed as much as one day with a ΔV penalty of only 7-8 m/s. However, a delay of less than 8 hours for E21+apo22 TCM and less than 6 hours for E24+apo26 leads to ΔV penalties of more than 60 m/s, loosely considered to be a limit for recoverability. TCM delay analyses for the BPM and JOI deterministic maneuvers have not been done yet. However, experience shows that while delaying the BPM as many as several days may not be detrimental, even a very short delay of JOI will result in loss of the mission.

Conclusion

The overall statistical ΔV estimate obtained in this study (including a 20 m/s budget for the orbital phase) is 217 m/s. This is approximately 10% of the current deterministic ΔV of 2000 m/s (9902 trajectory). This estimate is slightly above, but still within an acceptable range of the initial statistical ΔV estimate of 200 m/s. Currently, there are other tour/endgame trajectories under consideration with overall deterministic ΔV estimates of 1800 m/s (including cruise phase). These have shortened endgames with 4 less satellite flyby's (3 flyby's instead of 7), and 2 less deterministic ΔVs. This leads to approximately 10 less statistical TCMs, 2 for deterministic ΔV clean-ups and 2 per satellite encounter (pre/post encounter TCMs). Since the deterministic ΔV estimate is reduced by approximately 200 m/s (from 2000 to 1800 m/s), it is reasonable to assume the statistical ΔV may go down as well. This will put the overall statistical ΔV estimate closer to the 200 m/s initial budget. It should also be noted that of all the small variations made in the assumptions used in this study, none has resulted in a significant change in the overall statistical ΔV estimate. That is, the current best estimate seems to be stable around the 200 m/s value.

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